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ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES - CAPABILITIES, POTENTIALS AND CHALLENGES

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INTRODUCTION

For many years, electroactive polymers (EAP) received relatively little attention due to the small number of available materials and their limited actuation capability. The recent emergence of EAP materials with large displacement response changed the paradigm of these materials and their potential capability. The main attractive characteristic of EAP is their operational similarity to biological muscles, particularly their resilience and ability to induce large actuation strains. Unique robotic components and miniature devices are currently being explored, where EAP serve as actuators to enable new capabilities.

Generally, the low density and the relative ease of shaping them make polymers highly attractive materials and they are increasingly being chosen for aerospace applications. Early applications included components and structures, where composite materials made a significant impact on the construction of high performance aircraft. Increasingly, the resilience of polymers is finding applications in the emerging field of inflatable structures. Balloons were used to cushion the deployment of the Mars Pathfinder lander on July 4, 1997, paving the way for the recent large number of related initiatives. Inflatables are now being used to construct a rover (Figure 1), aerial vehicles, telescopes (Figure 2), radar antennas, and others. Some of these applications have reached space flight experiments, whereas others are now at advanced stages of development. Polymers were also reported as construction elements of such actuators as:

(a) McKibben muscle actuators [Schulte, 1961] – These are air tubes with an angularly breaded fiber reinforcement that contract significantly when inflated, delivering a large force.
(b) Shape memory polymers – These materials sustain a volume change of over 40 times when subjected to pressure and heat, and a temperature rise causes the recovery of the pre-pressed shape [Sokolowski, et al, 1999];
(c) Electrorhological fluids – These are electroactive polymer liquids that that experience dramatic changes in rheological properties in the presence of an electric field. Willis M. Winslow first explained the effect in the 1940s using oil dispersions of fine powders [Winslow, 1949]. The fluids are made from suspensions of an insulating base fluid and particles on the order of one tenth to one hundred microns in size. The electro-rheological effect is thought to arise from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to an induced dipole moment, will form chains along the field lines. This induced structure changes the ERF's viscosity, yield stress, and other properties, allowing the ERF to change consistency from that of a liquid to something that is viscoelastic with response times on the order of milliseconds.

Polymers with electroactive reaction with potential practical applications have emerged only in this decade with the introduction of EAP materials having significant displacement levels. These materials are highly attractive for their low-density materials with large strain capability that can be as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Also, these materials are superior to shape memory alloys (SMA) in their spectral response, lower density, and resilience. However, these materials reach their elastic limit at low stress levels, with actuation stress that falls far shorter than EAC and SMA actuators.

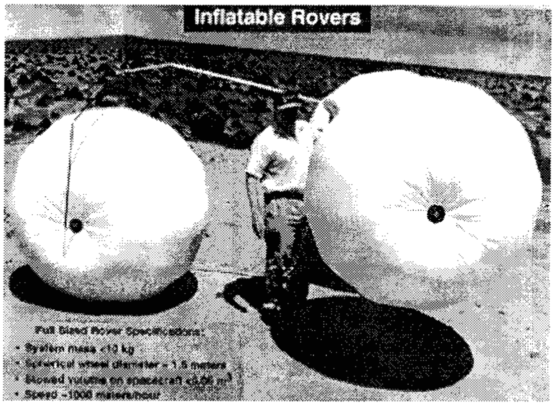


FIGURE 1: JPL rover using inflatable wheels (J. Jones, the Task Manager, is shown in the photo).

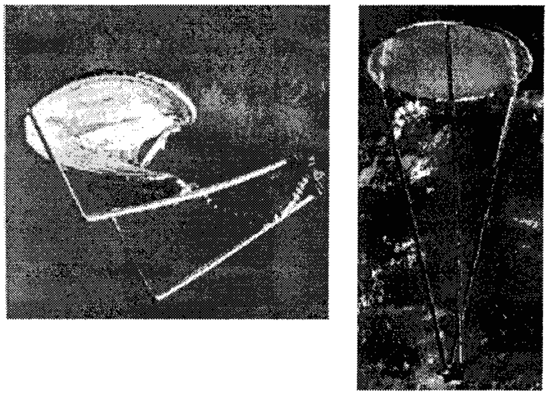


FIGURE 2: A Space Shuttle view of an inflatable structure experiment (May 1996). Left – During inflation and Right – Fully open.

A comparison between EAP, EAC (electroactive ceramics) and SMA (shape memory alloys) is given in Table 1 and it is easy to see the superior displacement actuation capability of EAP. EAPs are typically electrically hard and mechanically soft. Namely, ferroelectric polymers have a coercive field in the range of 100 MV/m, which is of the order of 100 times the coercive fields of ceramic ferroelectrics making polymers quite stable electrically. On the other hand, these materials reach their elastic limit at lower stress levels compared to the piezoelectric ceramics. Also, the actuation stress falls far shorter than EAC and SMA actuators.

TABLE 1: Comparison of the properties of some actuation materials

Property	Electro-static silicone elastomer [Kornbluh]	Polymer Electrostrictor [Zhang]	SMA	Single Crystal Electrostrictor [Shrout]	Single Crystal Magnetostrictor [Clark]
Actuation strain	32 %	4 %	8 %	1.7 %	2 %
Blocking Force/Area *	0.2 MPa	0.8 MPa	700 MPa	65 MPa	100 MPa
Reaction speed	μsec	μsec	sec to min	μsec	μsec
Density	1.5 g/cc	3 g/cc	6 g/cc	7.5 g/cc	9.2 g/cc
Drive field	144 V/μm	150 V/μm	--	12 V/μm	2500 Oe
Fracture toughness	large	large	large	low	large

*Note: Values were calculated assuming the elastic properties were independent of applied field and are therefore approximate.

The most attractive feature of EAPs is their ability to emulate biological muscles with high toughness, large actuation strain and inherent vibration damping. This similarity gained them the name "Artificial Muscles" and offers the potential of developing biologically inspired robots. Such biomimetic robots can be made highly maneuverable, noiseless and agile, with various shapes. Effective EAP offers the potential of making science fiction ideas a faster reality than would be feasible with any other conventional actuation mechanisms. Unfortunately, the force actuation and mechanical energy density of EAPs are relatively low, limiting the potential applications that can be considered at the present time. To overcome this limitation there is a need for development in numerous multidisciplinary areas from computational chemistry, comprehensive material science, electromechanic analysis and improved material processing techniques. Efforts are needed to gain a better understanding of the parameters that control the electromechanical interaction. The processes of synthesizing, fabricating, electroding, shaping and handling will need to be refined to maximize their actuation capability and robustness.

In recognition of the need for international cooperation among the developers, users and potential sponsors, the author organized though SPIE International the first EAP Conference on March 1-2, 1999. The Conference was held in Newport Beach, California, USA and was the largest ever on this subject making an important milestone and turned the spotlight onto these emerging materials and their potential. Following this success, MRS conference was initiated to address the fundamental issues related to the material science of EAP. Further, the author initiated the publication of the electronic WW-EAP Newsletter that was published in 2 issues by the end of the second Millennium (http://eis.jpl.nasa.gov/ndeaa/nasa-nde/newsltr/WW-EAP_Newsletter.PDF). He also established a homepage linking websites of worldwide EAP research and development facilities websites (http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm).

The increased level of resources, the grows in number of investigators that are conducting research in this field, the improved collaboration among the developers, users and sponsors are all expected to foster rapid progress in the coming years. Recently, the author challenged the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win a wrestling match with a human opponent (Figure 4). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, leading to a "bionic human." A remarkable contribution of the EAP field would be to one day seeing a handicapped person jogging to the grocery store using this technology.

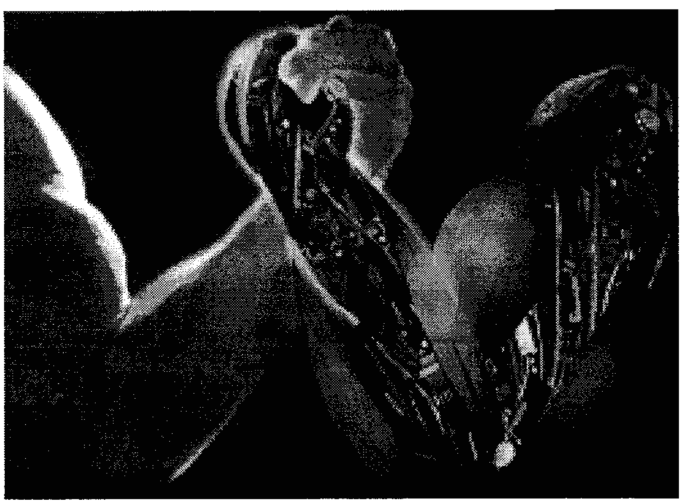


FIGURE 3: Grand challenge for the EAP community.

NEED FOR AN ESTABLISHED EAP INFRASTRUCTURE

Construction of a mobile or an articulation system that is actuated by EAP requires components as shown in the block diagram of Figure 4. While each of the listed components is at various research phases, EAP actuators are the least developed technology in this diagram and extensive efforts are required as discussed in this manuscript. Unfortunately, the materials that have emerged so far are still exhibiting low force and/or very slow response, and are far from being effective. Moreover, there are no commercially available robust EAP materials that can be considered for application in practical devices. In recent years, a series of EAP materials that induce large displacements were documented, including ion exchange membranes, gel polymers, conductive polymers, as well as electrostrictives, electrostatics and piezoelectrics [Bar-Cohen, 1999a]. In order to be able to transition these materials from a development phase to effective actuators there is a need to establish an adequate "infrastructure". The author's view of this infrastructure and the areas needing simultaneous development are shown schematically in Figure 5. There is a need for an adequate understanding of EAP materials' behavior and the requirements necessary to assure their durability under various service conditions. Further, enhancing their actuation force will require understanding the basic principles, development of computational chemistry models,

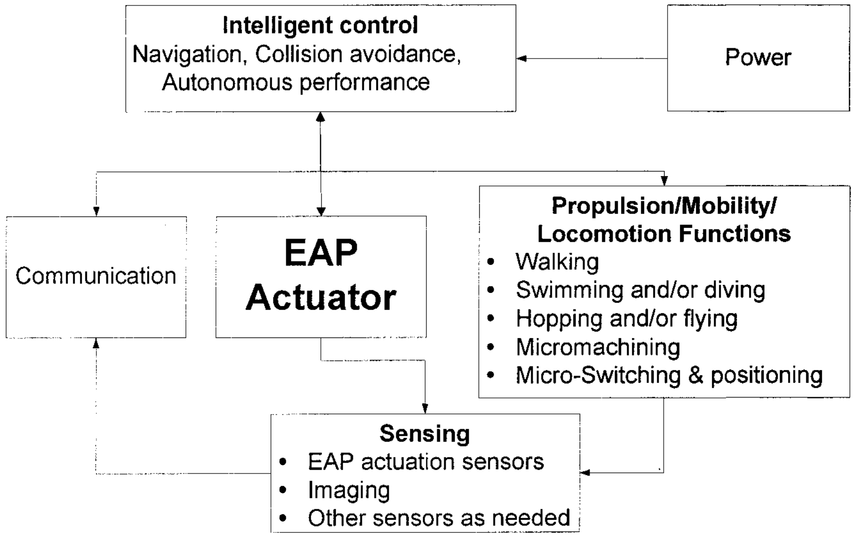


FIGURE 4: A schematic diagram of the basic components of an EAP-driven system.

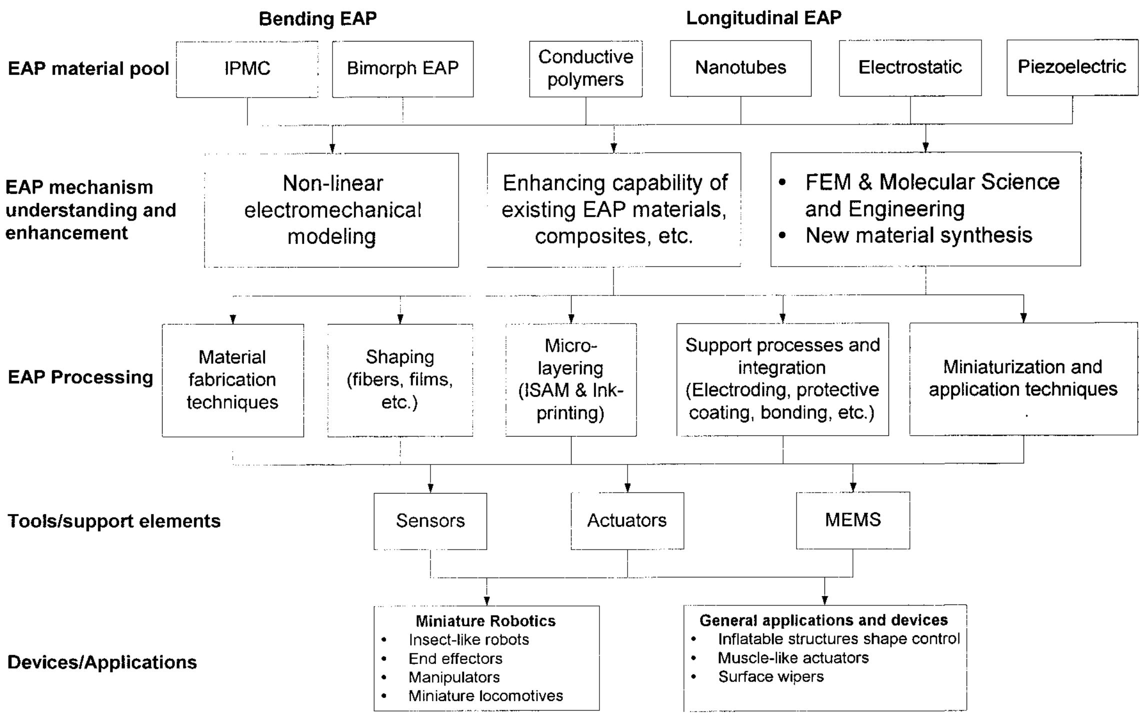


FIGURE 5: EAP infrastructure and areas needing attention.

comprehensive material science, electro-mechanic analytical tools and improved materials processes. Efforts are needed to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling will need to be refined to maximize their actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to allow documenting the material properties to support design engineering and making EAP the actuators of choice. Various configurations of EAP actuators, sensors and potential MEMS will need to be studied and modeled to produce an arsenal of effective actuators. The development of the infrastructure is multidisciplinary and requires international collaboration.

BIOLOGICAL MUSCLES AND SCIENCE FICTION

Development of intelligent robots requires the combination of strong muscles (actuators) and acute sensors and producing effective artificial muscle necessitates understanding the biological ones. Using effective EAP materials, so-called artificial muscles, one can develop biologically inspired robots and locomotives that can walk, fly, hop, dig, swim and/or dive. Natural muscles are driven by a complex mechanism and are capable of lifting large loads at short (millisecond) response times. The performance characteristics of muscles are difficult to measure and most measurements were made on large shell-closing muscles of scallops. Peak stress of 150-300-KPa is developed at a strain of about 25%. Maximum power output is 150 – 225-W/kg; average power is about 50-W/kg with an energy density of 20-70-J/kg, which decreases with the increase in speed. Since muscle is fundamental to animal life and changes little between species, we can regard it as a highly optimized system. It is system that depends on chemically driven reversible hydrogen bonding between two polymers, actin and myosin. Muscle cells are roughly cylindrical, with diameters between 10 and 100-μm and up to few centimeters long. Although muscles produce linear forces, motions at joints are all rotary. Therefore the strength of an animal is not just muscle force, but muscle force as modified by the mechanical advantage of the joint [Alexander, 1988], which usually varies with joint rotation (as does the muscle force). The mechanical energy is provided by a chemical free energy of a reaction involving adenosine triphosphate (ATP) hydrolysis. The release of Ca^{+2} ions seems turning on and off the conformational changes associated with muscle striction.

Insects mobility is under extensive study and there is a relatively large body of knowledge in place, as for example at the University of California, Berkeley [Full and Tu, 1990]. A windmill was used with a photoelastic coating (Figure 6) to study the details of insects walking mechanisms, where insects with various numbers of legs were investigated. Also, the size of electronic devices has become so small that insects can be instrumented to perform tasks once viewed as science fiction. At the University of Tokyo, Japan, a spider and other insects were instrumented as locomotives to carry backpacks of wireless electronics (Figure 7). Development in EAP actuators is expected to enable insect-like robots (Robosects) that can be launched into hidden areas of structures (e.g., aircraft engine) to perform inspection and various maintenance tasks. In future years, EAP may emulate the capabilities of terrestrial creatures with integrated multidisciplinary capabilities to launch missions with innovative plots. Some biological functions that can be adapted include soft-landing like cats, traversing distances by hopping like a grasshopper and digging and operating cooperatively as ants (Figure 8).

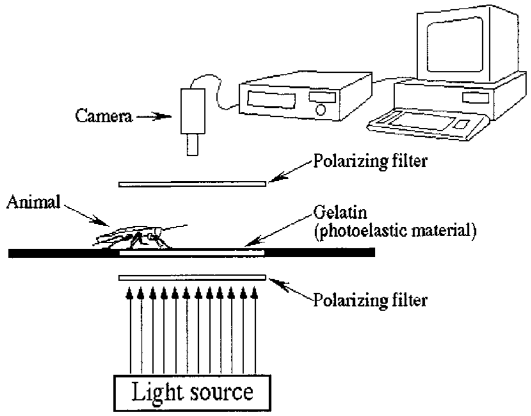


FIGURE 6: A Schematic view of the UC Berkeley's test system for insect walking http://rjf2.biol.berkeley.edu/Full_Lab/FL_Publications/PB_Posters/94ASZ_Turning/94ASZ_Turning.html

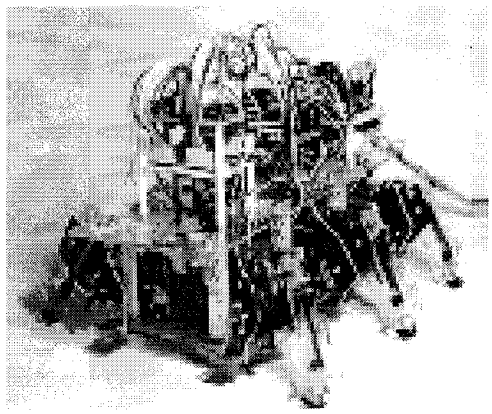


FIGURE 7: An instrumented spider at the University of Tokyo illustrates the potential to NDE in terms of mobile sensors [http://www.leopard.t.u-tokyo.ac.jp/].

As a scenario for futuristic missions - multiple Robosects can be designed to search for evidence of former/existing life, resources, rare minerals and the presence of water, determine magnetic and other forces, reach crevices, construct miniature fixtures, examine the geophysics, carry relays for remote communication as well as perform unique experiments. Sensing options such as smelling and tasting, using chemical sensors equivalent biological ones, can be considered. Robosects can be equipped with various practical locomotion techniques, such as hopping and flying to traverse large distances, crawling to reach specific locations, as well as digging tunnels for underground operations. At low gravity and low ambient pressures, particularly on small bodies, hopping offers an effective form of traversing long distances. On wet planets and moons, such as Europa, swimming and diving options can be added. The development of a cooperative colony will offer redundancy allowing for the execution of tasks that are significantly beyond the capability of individual Robosects. Moreover, the option of "maintenance/emergency crews" can be explored. Ant colonies are an excellent model for cooperative Robosects and it is not unusual to see a group of ants carrying a large leaf, which is considerably larger and heavier than they are individually. Moreover, Robosects can be designed to perform self-cleaning for dust removal from their solar cells to avoid losing the power-generating capability as can be encountered on Mars. The possibility of self-cloning can also be explored.

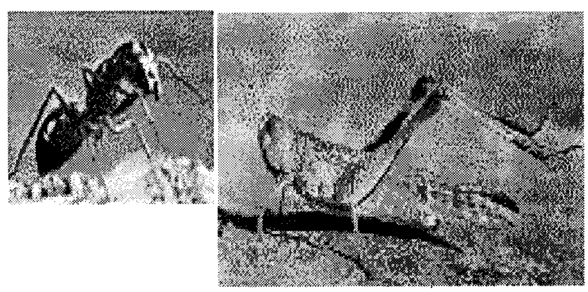


FIGURE 8: Robosect colonies that emulate insect capabilities and behavior offer exciting future NASA missions.

CURRENTLY AVAILABLE EAP MATERIALS

The field of electroactive polymers was established with the discovery of an electret when carnauba wax, rosin and beeswax is solidified by cooling while subjected to DC bias field [Eguchi 1925]. Following the 1969 observation of a substantial piezoelectric activity in PVF2, investigators started to examine other polymer systems and a series of applications have emerged. In recent years, the list of new EAP materials has grown considerably, however the is still only one commercially available one and it is based on PVF2/TRFE materials. In recent years, a growing number of EAP materials have with large actuation displacement were report and their drive mechanisms include chemical [Kuhn, et al, 1950; and Steinberg, et al, 1966], thermal [Tobushi, et al, 1992; and Li, et al, 1999], electrical [Perline, et al, 1998, and Zhang, et al, 1998, magnetic [Zrinyi, et al, 1997, and Bednarek, 1998], and optical [van der Veen & Prins, 1971]. In many cases a combination of forces (e.g. electrochemical [Otero, et al, 1995]) is required to induce mechanical actuation. Half a century ago, [Kuhn el al, 1950] demonstrated that collagen filaments reversibly contracted or expanded when dipped in acid or alkali aqueous solutions, respectively. Although very little has since been done to exploit such 'chemomechanical' actuators [Kuhn, et al, 1960, and Sussman, 1975], this early work pioneered the growth of a wide variety of bio-mimicking synthetic polymers.

IONICALLY CONDUCTING POLYMERS (ICP)

Ionically conducting polymers [Otero, et al, 1995, Tanaka, et al, 1982, and Abe, et al, 1998] are materials containing solvated ions that swell in response to applied voltages. The conformational changes are due to electrophoresis or electro-osmotic drag. Swelling of the polymer can occur even in the absence of applied fields as a result of sorbtion of solvents (usually water). Electrochemical reactions (oxidation/reduction) occur at electrodes that either promote or hinder actuation. Most reported actuators that were formed using ICP material exploited the voltage controlled swelling were formed as benders. The required voltage may vary from 1-mV to 50-V and the response time depends on thickness, diffusivity, kinetics of electrochemical reactions etc. and it can vary from milliseconds to minutes. Protective skins must be developed in order for these materials to be active in dry environments. The use of polar low vapor pressure solvents (such as propylene carbonate) helps to extend the ICP ability to perform in harsh conditions. Actuators that are based on ICP have limited driving force capability and they are typically less than 1-g.

A series of conductive polymers that are currently investigated for actuation capability include: Polypyrrole, Polyaniline (PANi), Polythiophenes, Polyethylenedioxythiophene, Poly(p-phenylene vinylene)s.

IONIC POLYMER METALLIC COMPOSITE (IPMC) AS BENDING ACTUATOR

IPMC are films that bend under stimulation by electric currents induced by relatively low voltages. The ionic content of the IPMC is an important factor in the electromechanical response. Results using sodium cations and platinum metallization are shown in Figures 1-3 [Shahinpoor, et al, Dec. 1998]. Enhanced capabilities were reported by [Yoshiko, et al, 1998 and Oguro, et al, 1999] using Li+/gold and other types of cations. IPMC as an EAP material was realized in the early 1990's by [Oguro, et al, 1992] in Japan, and by [Sadeghipour, *et al*, 1992] and [Shahinpoor, 1992] in the United States. This material consists of chemically treated Nafion and it induces large bending deformation in the presence of low voltage. In order to chemically electrode IPMC's, metal ions (Platinum, gold or others) are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero valent metal atoms.

The bending EAP actuator is composed of perfluorinated ion exchange membrane platinum composite (IMPC), where platinum electrodes are deposited on both sides. The actuator is based on a processed Nafion film having the following chemical formula,

$[-(CF_2-CF_2)_n-CF-CF_2-]_m$
|
$O-CF-CF_2-O-CF_2-SO_3-M$
|
CF_3

where n ~ 6.5, 100 < m < 1000, and M^+ is the counter ion (H^+, Li^+, Na^+ or many others). The structure and properties of the IMPC have been the subject of numerous investigations (see for example [Heitner-Wirguin, 1996]). One of the interesting properties of this material is its ability to absorb large amounts of polar solvents, i.e. water. In order to chemically electrode the IMPC, platinum (Pt) metal ions are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero valent metal atoms. This results-in the formation of a dendritic type electrodes. A scanning electron micrographic tests show [Bar-Cohen, et al, 1997] that the Pt metal covers each surface of the film with some of the metal penetrating the subsurface regions of the material. When equilibrated with aqueous solutions the ionomer membrane is swollen to absorb certain amount of water. Swelling equilibrium results from the balance between the elastic forces of the polymeric matrix and the water affinity to the fixed ion-exchanging sites and the moving counter ions. The water content depends on the hydrophilic properties of the ionic species inside the membrane and also on the electrolyte concentration of the external solution.

Its ionic polyelectrolyte is for the most part a 3-D network of macromolecules cross-linked with ionic charge groups nonuniformly distributed within the polymer matrix [Shahinpoor, 1994; and Heitner-Wirguin, 1996]. The mechanism of bending is partially related to migration of mobile ions within the networks caused by an applied electric field. The structure and properties of IMPCs have been the subject of numerous investigations (e.g., [Heitner-Wirguin, 1996]). Recent investigation by [Firoozbakhsh & Shahinpoor, 1998], suggests a strong interaction effect of surface charges. Since the actuation capability of IPMC is attributed to its ionic content, it is necessary to continuously maintain its moisture. A process developed at NASA-LaRC allowed the formation of a protective coating which serve as the equivalence of a biological skin, and was demonstrated to effectively maintained the moisture for several months [Bar-Cohen, et al, 1998].

Under a relatively low voltage a large bending displacement is observed reaching saturation at values of ~4-volt, and a force to weight ratio of 40 was measured. As can be see in Figure 1, the displacement depends on the voltage and the frequency, where lower frequencies (~0.1 Hz) lead to higher displacements (approaching 25-mm for a 25x6x0.1mm strip). The displacement reaches maximum amplitude at the resonant frequency, beyond which the response starts diminishing (>50Hz for 25mm long strip). Figure 2 were showing a pair of films that were connected to behave as a muscle, where under 4-Volts contracted by >11%, while consuming <.2-W. Since IPMC films are made of a relatively strong material with a large bending capability, they were used to emulate fingers and 4-gripper was developed (Figure 3). Such a gripper can serve as an end-effector of a miniature low-mass robotic arm. The fingers bend either inward or outward, similar to the operation of a hand, and hooks at the end of the fingers acting as nails securing gripped objects held by the fingers. The large bending capability of IPMC also enabled the fabrication of a surface wiper, operating similar to windshield wiper but with no mechanism (i.e., gear, motor, etc.). Example of the surface wiper is shown in Figure 4. This wiper is currently being considered for use to support the Jet Propulsion Laboratory Nanorover on the MUSES-CN mission to an asteroid and is expected to be launch in 2002. Recent performance tests at low temperatures showed that while the response decreases with temperature, a sizeable displacement was still observed at -140°C at vacuum of 1-torr. The decrease in actuation displacement can be compensated by increasing the voltage and it is interesting to point out that at low temperatures the response reaches saturation at a higher voltage level (~7-V at -100°C).

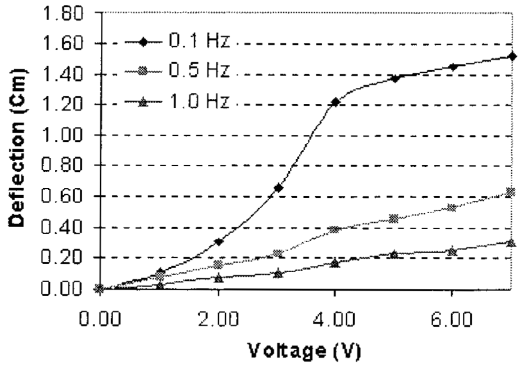


Figure 1: Typical response of Na+/Pt IPMC at various voltage levels and 3 frequencies.

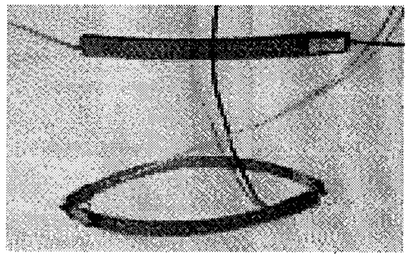


Figure 2: Na+/Pt IPMC film-pair. Top: reference, Bottom: activated

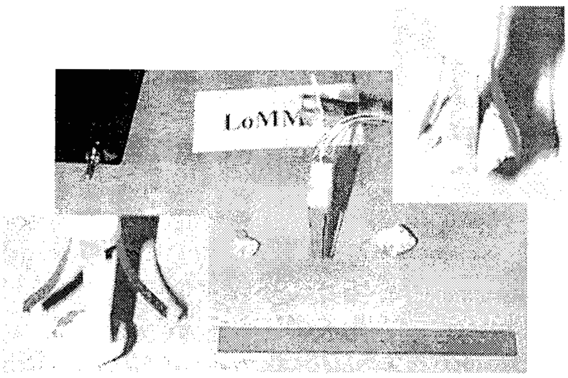


Figure 3: Four-finger gripper lifting >10-g rock using 0.1-g fingers.

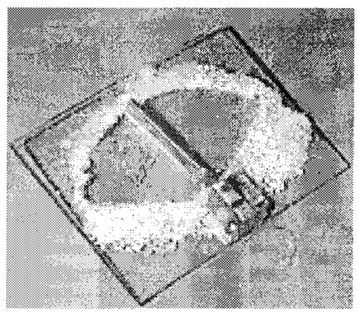


Figure 4: A dust wiper consisting of a Li+/Gold bending electroactive polymer and with a miniature blade (made by ESLI, San Diego, CA).

Driving a dust wiper using EAP materials requires that material be capable of bending under electro-activation. As can be seen in the first issue of the WW-EAP Newsletter [Bar-Cohen, 1999b], several types of EAP materials can be made to bend under electrical excitation. The authors concentrated on the use of the ion exchange polymer membrane metal composite (IPMC) which has metal electrodes deposited on both sides. Two types of base polymers were used including Nafion® (perfluorosulfonate made by DuPont) and Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). Prior to using these polymers as EAP base material, they were widely employed in fuel cells and production of hydrogen (hydrolysis). The operation as actuators is the reverse process of the charge storage mechanism associated with fuel cells. In the current study, Nafion® #117 was used with a thickness of 0.18-mm and perfluorocarboxylate films were used having a thickness of 0.14-mm. Initial studies involved the use of Platinum as the metal electrodes however recent studies have shown that gold coating provides superior performance [Yoshiko, et al, 1998]. The gold layer was applied in 7-cycles resulting in a dendritic structure as shown in a cross section view in Figure 4. The counter cation consists of tetra-n-butylammonium or lithium and these two species showed significantly greater bending response than sodium, which was used earlier. Under less than 3-V, such IPMC materials were shown to bend beyond a complete loop and the response follows the electric field polarity.

When an external voltage is applied on an IPMC film, it causes bending towards the anode at a level that increases with the voltage, up until reaching saturation, as shown in Figure 5. Under AC voltage, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Generally, activation at lower frequencies (down to 0.1 or 0.01 Hz) induces higher displacement and the displacement diminishes as the frequency rises to several tens of Hz. The drive voltage level at which the bending displacement reaches saturation depends on the frequency and it is smaller at higher frequencies. The applied electrical current controls the movement of the film but the response is strongly affected by the water content of the IPMC serving as an ion transport medium.

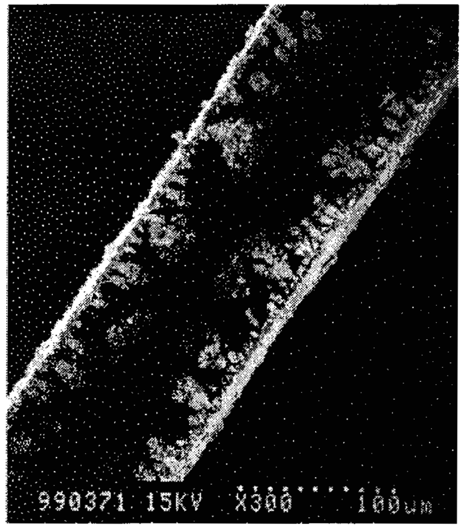


FIGURE 4: Perfluorocarboxylate membrane with tetra-n-butylammonium cation and 7 cycles of ion exchange and reduction (resulting dendritic growth) of the gold electrodes.

The authors addressed several issues that were determined critical to the application of IPMC (both the Nafion® and Flamion® base):

Film moisture: IPMC is highly sensitive to its moisture content. To maintain the moisture content there is a need for a protective coating that acts as the equivalent of skin, otherwise the material stops to respond after few minutes of activation in dry conditions. Using an etching procedure and silicon coating, an IPMC film was shown to operate for about 4 months. This Dow Corning coating material allows operation in a wide range of temperatures with great flexibility and is durable under UV radiation. However, since the MUSES-CN mission requires operation over 3-years, the 4-month protection period is too short. Analysis of the cause of the degradation indicates that the silicon coating is water permeable and the rate is *3000* cm^3 *x* 10^{-9} *per sec/*cm^2*/cm* at STP and 1 cm•Hg pressure difference [Dow Corning, 1999]. Assuming 2 cm^2 electrode area with 0.1-mm thick silicone coating shows a water loss rate of ~40-50mg/24 hrs. This rate is significantly higher than observed for IMPC and it does not account for the IPMC electrode layers, however it indicates the severity of the issue. To overcome this limitation various alternative coating techniqus are being considered including the use of a metallic Self-Assembled Monolayer as an overcoat.

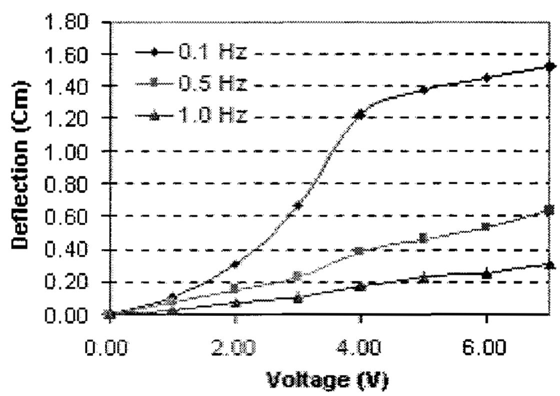


Figure 5: The response of the bending EAP to various voltage amplitudes at three

Electrolysis: The wetness of IPMC and the introduction of voltages at levels above 1.03-V introduce electrolysis during electro-activation causing degradation, heat and release of gasses. This issue raises a great concern since the emitted hydrogen accumulates under the protective coating and leads to blistering, which will rupture the coating due to the high vacuum environment of space. The use of tetra-n-butylammonium cations was shown to provide higher actuation efficiency allowing to reduce the needed voltage and to minimizing the electrolysis effect.

Operation in vacuum and low temperatures: In space the temperature can drop to significantly low levels and the ambient pressure is effectively vacuum. The ability to protect IPMC from drying allowed performing tests in vacuum and low temperatures. These tests showed that while the response decreases with temperature, as shown in Figure 6, a sizeable displacement was still observed at -140°C. This decrease can be compensated by an increase in voltage. It is interesting to point out that, at low temperatures, the response reaches saturation at much higher voltage levels.

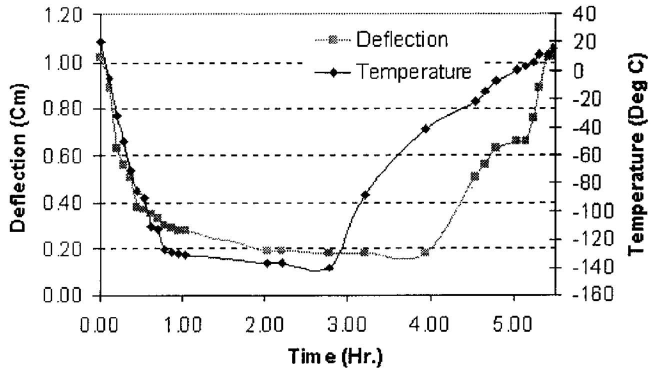


Figure 6: Deflection amplitude of sodium-base IPMC as a function of time and temperature.

Besides the need to address the low temperature issue, the material ability to sustain temperatures as high as +125°C is also necessary. For this purpose, several solvents with higher boiling points than water were examined for their potential use as a solvent for the IPMCs. This solvents were examined for their performance equivalence to "antifreeze" in automobile radiators. Various solvents were considered and their effect on the swelling characteristics of Nafion® was investigated. Nafion® strips with an initial size of 5.8mm x 38.1mm were immersed in a series of solvents for a period of 4-days at ambient temperature and the change in mass and size were measure. Examination of IPMC films that were immersed for 24-hours in various solvents, including ethylene glycol, showed a significant reduction in the induced bending amplitude.

Low actuation force: Using thin IPMC with a thickness of 0.14-mm was found to induce a significant bending displacement. However, the induced force was found relatively small making it difficult for the wiper to overcome the electrical forces that are involved with the dust-repelling high-voltage. Further, even though the wiper blade is relatively light, weighing about 104-mg, it is still responsible for significant bending due to gravity pressing the blade onto the window surface and constraining its movement. Alternative 0.18-mm thick film is currently being sought to provide the necessary force.

Permanent deformation under DC activation: Unfortunately, under DC voltage IPMC strips do not maintain the actuation displacement and they retract after several seconds. Further, upon removal of the electric field an overshoot displacement occurs in the opposite direction moving slowly towards the steady state position leaving a permanent deformation. This issue was not resolved yet and would hamper the application of IPMC.

Challenges and solutions: To allow future design of EAP mechanisms actuated by IPMC, the challenges and solutions were summarized and are listed in Table 2. While most challenges seems to have been addressed, two issues still pose a concern: the introduction of permanent deformation and the need for an effective protective coating. Unless these issues are effectively resolved the use of IPMC for planetary applications will be hampered.

TABLE 2: Challenges and identified solutions for issues regarding the application of IPMC.

Challenge	Solution
Fluorinate base - difficult to bond	Pre-etching
Sensitive to dehydration (~5-min)	Etching and coating
Electroding points cause leakage	Effective compact electroding method was developed
Off-axis bending actuation	Use of load (e.g., wiper) to constrain the free end
Most bending occurs near the poles	Improve the metal layer uniformity
Electrolysis occurs at >1.03-V in Na+/Pt	• Minimize voltage • Use IPMC with gold electrodes and cations based on Li^+ or Perfluorocarboxylate with tetra-n-butylammonium
Survive -155°C to +125°C and operate at -125°C to + 60°C	IPMC was demonstrated to operate at -140°C
Need to remove a spectrum of dust sizes in the range of >3μm	• Use effective wiper-blade design (ESLI, San Diego, CA) • Apply high bias voltage to repel the dust
Reverse bending under DC voltage	Limit application to dynamic/controlled operations
Developed coating is permeable	• Alternative polymeric coating • Metallic Self-Assembled Monolayer overcoat
Residual deformation	Still a challenge
No established quality assurance	• Use short beam/film • Efforts are underway to tackle the critical issues

IONIC GEL EAPS

Synthetic ionic gel actuators have the potential of matching the force and energy density of biological muscles when driven chemically, usually by changing from an acid to base environment the gel becomes dense or swollen, respectively. However, the response is slow because of the need to diffuse ions into the gel and it takes with the current capability about 20-min to complete the displacement actuation.. Recent studies at the University of Arizona have shown that this response can be activated electrically (see Figure 6). When driven by embedded electrodes, these gels bend as the cathode side becomes more basic and the anode side more acidic.

ELECTRO-STATICALLY STRICTED POLYMER (ESSP) ACTUATORS

Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field. This characteristic allows producing longitudinal actuators that operate similarly to biological muscles using Coulomb forces between electrodes to squeeze or stretch the material. Following efforts by [Kornbluh, et al, 1995; and Perline, et al, 1998] longitudinal electrostatic actuators are made of a dielectric elastomer films and flexible electrodes. To produce a longitudinal actuator with large actuation force, two silicone layers was used with carbon electrodes on both sides of one of the layers. Wrapping the film to the shape of a rope allows making an actuator that can lift objects as shown in Figure 5. Besides using ESSP in the form of ropes that are bundled to further mimic human muscle, bending actuators can be constructed by adding a passive backing layer on one side of the electroactive film. To enhance the capability of this type of actuator, while making it contractile, studies are underway to produce EAP fibers that would be bundled to emulate muscles.

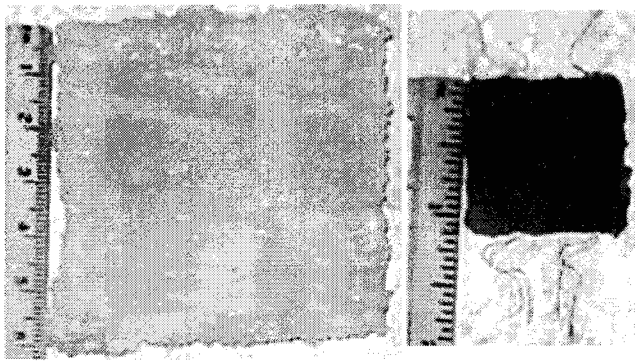


Figure 6: Gel containing 4-pairs of electrodes swollen (left, 6-cm) and contracted (right, 3-cm).

ESSP actuation force

A schematic diagram of an ESSP actuator is show in Figure 5-left, and it can be represented by a parallel plate capacitor. The strain S and stress T developed when an electric field E is applied is given by:

$$S = -\frac{1}{2Y}\varepsilon_o \varepsilon E^2 \qquad (1)$$

$$T = -\frac{1}{2}\varepsilon_o \varepsilon E^2 = YS \qquad (2)$$

where: Y is the Young's modulus of the dielectric between the plates with relative permittivity ε (dielectric constant); ε_0 is the permittivity of vacuum and ε is the relative permittivity; and E is the electric field across the thickness of the film,. It can be seen that the effect of adding elastic dielectric material between the plates of the capacitor is to both increases the charge density and prevent the plates from shorting. The factor of ½ arises because the charge is contained only at the surface of the charged plates and the average electric field acting on this charged layer is $E/2$. It is important to note that the induced strain varies quadratically (nonlinear) with applied field. In 1880 Roentgen provided an early example of this effect by charging and discharging rubber bands with one end fixed and a mass attached to the free end. The force (stress) that is exerted on such a film with compliant electrodes is:

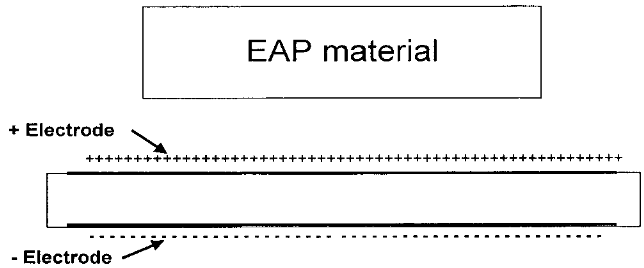
$$P = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V / t)^2 \qquad (3)$$

Where: P is the normal stress, V is the voltage applied across the film and t is the thickness of the film. The Poisson's ratio is assumed as 0.5.

Use of polymers with high dielectric constants and application of high electric field leads to large forces and strains. To reach the required electric field levels one needs to either use high voltage and/or employ thin films. Under an electric field the film is squeezed in the thickness direction causing expansion in the transverse direction (See Figure 5-left). For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the following relation, where the second order components are neglected.

$$\Delta D / D_0 = (1/2)\Delta t / t_0 \tag{4}$$

Where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change; t_0 is the original thickness; and Δt is its change under electric activation.



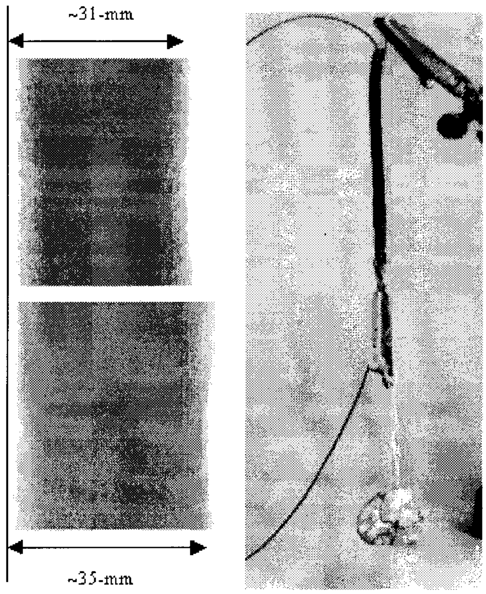


Figure 5: Left - Under electro-activation, an EAP film with electrodes on both surfaces expands laterally. Middle - EAP film subjected to 25 V/μm induced over12% extension. Right - A >10-g rock mounted at the end of an EAP rope is lifted and dropped electrically.

ESSP actuators are subject to a major concern associated with the required large electric fields (~100 V/μm) necessary to induce significant strains (~10%). The actuator has to be thin (<50μm) to assure the use of achieve reasonable voltages. Overall, the associated voltage levels are close to the breakdown strength of the material and, since the dielectric breakdown may be difficult to predict, a safety factor needs to be used when designing such actuators. Moreover, the relatively small breakdown strength of air (2-3 V/μm) presents additional challenge. Longitudinal actuators are produced using ESSP materials and they employ the Poisson effect that results from the film contraction. To obtain significant actuation displacements requires the use of large film material. Elastomers with Young's moduli on the order of < 20 MPa and relative permittivities of 3 can induce large strain at the level of 30%. The Young's modulus is fairly temperature independent until the glass transition temperature is reached, at which point a sharp increase occurs making them too stiff to be used as electrostatic actuators.

In the above case of the ideal parallel-plate capacitor, the Maxwell stress was due to the *uniform* electric field between the plates. Another type of Maxwell force exists when the dielectric particles are placed in *nonuniform* electric fields. Uncharged particles will always be attracted to the region of stronger field regardless if it is positive or negative polarity. This force is proportional to the gradient of square of the field as well as the permittivity of the object. A familiar example of this effect is the attraction between a comb, charged by brushing ones hair, and bits of paper. An analogous effect also exist for magnetic fields, where paramagnetic and ferromagnetic materials experience a force directed to stronger magnetic field (diamagnetic materials are actually repelled by the region of stronger field). Composite materials can be made of fine (~10 nm) ferri/ferromagnetic particles dispersed in silicone elastomers. With such elastomers strains as high as 40% can be achieved with force level of 0.1 N and maximum field intensity of 80 mT [Zrinyi, 1996]. The disadvantage of this type of actuators is the need to for either movable permanent magnets or an electromagnet with high currents.

FERROELECTRIC POLYMERS

Poly(vinylidene fluoride) (PVDF or PVF2) and its copolymers are the most widely exploited ferroelectric polymers. These polymers are partly crystalline, with the amorphous phase being inactive. They possess Young's moduli near 1-10 GPa. A large amplitude (~200 MV/m) applied AC field can induce electrostrictive (nonlinear) strains of nearly 2%. However this level of field is dangerously close to dielectric breakdown, and the dielectric hysteresis (loss, heating) is very large, thus limiting it's use in practical devices. Scheinbeim [Sen, 1984] has investigated the effect of heavily plasticizing (~65 wt. %) ferroelectric polymers hoping to achieve large strains at reasonable applied fields. However, the plasticizer is also amorphous and inactive, resulting in decreased Young's modulus, permittivity and electrostrictive strains. Recently, Zhang [1998] has introduced defects using electron radiation to reduce the dielectric loss dramatically in P(VDF-TrFE) copolymer. This permits AC switching with a lot less heat generated. As large as 4% electrostrictive strains can be achieved at low frequency drive fields of amplitudes ~150 V/μm. The elastic modulus of this material is 0.4 GPa, and therefore the mechanical energy density is quite large.

As with ceramic ferroelectrics, electrostriction can be considered as the origin of piezoelectricity in ferroelectric polymers [Furukawa, 1990]. A DC bias polarization can either be present via a *poling* process before use in a device, in which case a remnant polarization persists, or large DC electric field is applied during operation of the material in a device. In the latter case, no remnant polarization is observed when the bias is removed, and corresponds to a ferroelectric possessing a very small hystersis in the polarization-electric field loop. Unlike electrostriction, piezoelectricity is a linear effect. Not only will the material strain when voltage is applied, but a voltage signal will be induced when a stress is applied. This enables them to be used as sensors. Care must be given to not apply too large of applied voltage, mechanical stress, or high temperature for fear of de-poling the material.

ELECTRO-VISCOELEASTIC ELASTOMERS

Electro-viscoeleastic elastomers represent another family of electroactive polymers. These EAP materials are composites of silicone elastomer and a polar phase. Before crosslinking, in the uncured state, they behave as electro-rheological fluids. An electric field is applied during curing to orient and fix in position the polar phase in the elastomeric matrix. These materials then remain in the "solid" state but have a shear modulus (both real and imaginary parts) that changes with applied electric field (< 6 V/μm) [Shiga, 1993; and 1997]. A stronger magneto-rheological effect can also be introduced in an analogous manner and as much as a 50% change in the shear modulus can be induced [Jolly, 1996; and Davis,1999]. These materials may be used as alternatives to electrorheological fluids for active damping applications. To obtain precision control of robotic arms, with a closed-loop system, active damping is necessary.

DEVELOPMENT OF EAP UNDER JPL LEAD

Under the author's lead, planetary applications using EAP are being explored while improving the understanding, practicality and robustness of these materials. EAP materials are sought as a substitution to conventional actuation components such as motors, gears, bearings, screws, etc. This research and development effort has been conducted since 1995 under the NASA task of so-called Low Mass Muscle Actuator (LoMMAs), and the current team consists of JPL, NASA-LaRC, VT, Rutgers University, and ESLI having cooperative efforts with Osaka National Research Institute, Japan, and, Kobe University, Japan [Bar-Cohen, et al, 1999c].

Under the NASA task, longitudinal and bending EAP are being investigated for planetary applications, and a dust-wiper, gripper and robotic arm were demonstrated [Bar-Cohen, et al, 1999b]. The dust-wiper (Figure 9) is currently being developed for the Nanorover's optical/IR window, which is part of the MUSES-CN mission. The MUSES-CN is a joint NASA and Japanese Space Agency mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. The team is testing the use of highly effective ion-exchange membrane metallic composites (IPMC) made of perfluorocarboxylate-gold composite with two types of cations, tetra-n-butylammonium and lithium. Under a potential difference of less than 3-V, these IPMC materials are capable of bending beyond a complete loop. A unique ~100-mg blade with fiberglass brush was developed by ESLI (San Diego, CA) and subjected to a high voltage to repel dust, augmenting the brushing mechanism provided by the blade.

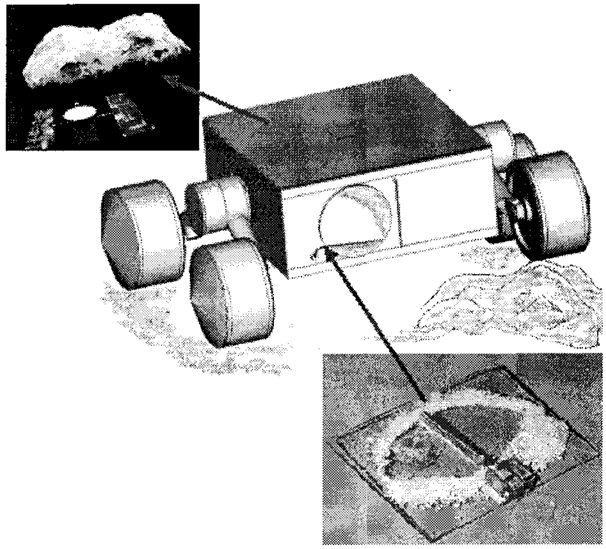


FIGURE 9: Schematic view of the EAP dust-wiper on the MUSES-CN's Nanorover (right) and a photograph of a prototype EAP dust-wiper (left).

Generally, space applications are the most demanding in terms of operating conditions, robustness and durability. The team is jointly addressing the associated challenges. Several issues that are critical to the operation of IPMC are examined, including its response in vacuum and low temperatures, as well as the effect of the material's electromechanical characteristics on its actuation capability. The use of highly effective IPMC materials, mechanical modeling, unique components and a protective coating are increasing the probability of success for the EAP-actuated dust-wiper. Another application of EAP actuators is the development of a miniature robotic arm with closed-loop control (Figure 10). A longitudinal EAP, based on SRI international developed actuator, is used to lift and drop the arm, whereas a 4-finger gripper is used to grab rocks and other objects. The EAP fingers operate much like a human hand when grabbing the rock as shown in Figure 11.

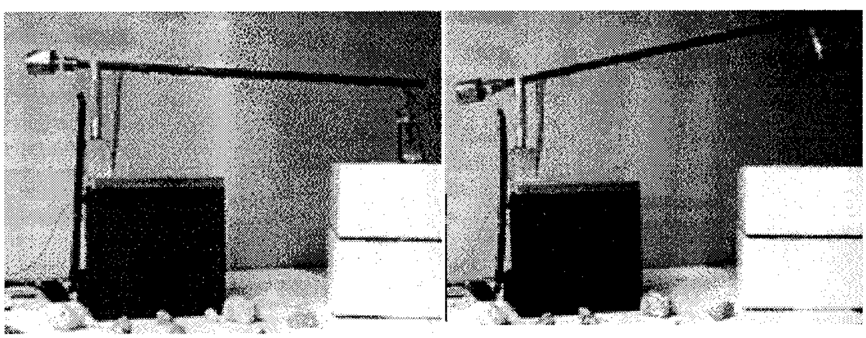


FIGURE 10: A miniature robotic arm using EAP actuators to provide the lifting/dropping of the arm and manipulate the gripper fingers.

Generally, the practical application of EAP materials is still a great challenge. No effective and robust EAP material is currently available commercially. Further, there is no established database that documents the properties of the existing EAP materials.

CONCLUDING REMARKS

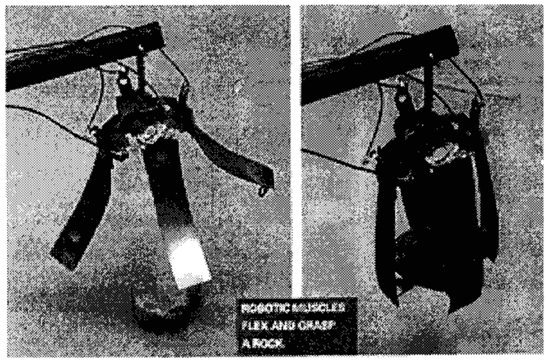


FIGURE 11: 4-finger EAP gripper lifting a rock much like a human hand (Discover, Vol. 19 No. 8 (August 1998), p. 33)

Electroactive polymers have emerged in recent years with great potential to enabling unique mechanisms that can emulate biological systems. Much more research and development work still needs to be done before EAP will become the actuators of choice. The development of an effective infrastructure for this field is critical to the commercial availability of robust actuation materials for practical applications. The challenges are enormous, but the recent international trend towards more cooperation and greater visibility to the field as well as the surge in funding and research offer great hope for the future of these exciting materials. Science fiction tasks will be transitioned to reality at an unprecedented rate once effective EAP materials become available.

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REFERENCE

Bar-Cohen, Y., (Ed.), *Proceedings of the Electroactive Polymer Actuators and Devices*, Smart Structures and Materials 1999, Volume 3669, pp. 1-414, (1999a).

Bar-Cohen, Y., S. Leary, M. Shahinpoor, J. Harrison and J. Smith, "Flexible Low-Mass Devices and Mechanisms Actuated by Electroactive Polymers," et al, pp. 51-56 (1999b).

Bar-Cohen, Y., K. Oguro, S. Tadokoro, S. Leary, J. Harrison and J. Smith "Challenges to the Transition of IPMC Artificial Muscle Actuators to Practical Application," Proceedings of the Fall MRS Meeting, (1999c).

Full, R.J., and Tu, M.S., "Mechanics of six-legged runners." J. Exp. Biol. Vol.148, pp. 129-146 (1990).

Schulte, H.F., "The Characteristics of the McKibben Artificial Muscle" Applications of External Power in Prosthetics and Orthotics, Appendix H, Publication 874, National Academy of Sciences, Washington, pp. 94-115, (1961).

Sokolowski, W. M., A. B. Chmielewski, S. Hayashi and T. Yamada, "Cold Hibernated Elastic Memory (CHEM) Self-Deployable Structures," Proceedings of the Electroactive Polymer Actuators and Devices, Smart Structures and Materials 1999, Volume 3669, Y. Bar-Cohen (Ed.), pp. 179-185, (1999).

Winslow, W. M., 1949, "Induced Fibrillation of Suspensions," *Journal of Applied Physics*, Vol. 20, pp. 1137.

Abe Y., A. Mochizuki, T. Kawashima, S. Yamashita, K. Asaka, and K. Oguro, "Effect of bending behavior of counter cation species in perfluorinated sulfonate membrane-platinum composite," *Polym. Adv. Technol.*, Vol. 9 (1998), pp. 520-526.

Alexander R. M., Elastic Mechanisms in Animal Movement, The Cambridge University Press: Cambridge, 1988.

Bar-Cohen Y., T. Xue, M. Shahinpoor, J. O. Simpson, and J. Smith, "Flexible, low-mass robotic arm actuated by electroactive polymers (EAP)," *Proceedings of the SPIE International Smart Materials and Structures Conference*," SPIE Paper No. 3329-07, San Diego, CA, 1-6 (March 1998).

Dario, P.," Transducers for advanced robotics," pp. 221-236 in Application of Ferroelectric Polymers. T.T. Wang, J.M. Herbert, and A. M. Glass (Eds.) New York: Chapman and Hall (1988).

Davis, L.C., "Model of magnetorheological elastomers," *J. Appl. Phys*, Vol.85, No.6 (1999), pp.3348-3351.

Eguchi M., Phil. Mag., Vol. 49, (1925)

F. K. Li, W. Zhu, X. Zhang, C. T. Zhao, and M. Xu, "Shape memory effect of ethylene-vinyl acetate copolymers," *J. Appl. Polym. Sci.*, Vol. 71, No. 7 (1999), pp. 1063-1070.

Firoozbakhsh, K., and M. Shahinpoor, "Mathematical Modeling of Ionic Interactions and Deformation," Proc. SPIE Smart Materials and Structures Conf., March 3-5, 1998, San Diego, CA, Publication No. SPIE 3323-66, (1998)

Furukawa and J. X. Wen, "Electrostriction and Piezoelectricity in Ferroelectric Polymers," Japanese Journal of Applied Physics, Vol. 23, No. 9, 1984, pp. 677-679.

Furukawa, T. and Seo, N., "Electrostriction as the origin of piezoelectricity in ferroelectric polymers," *Jpn. J. Appl. Phys*, Vol. 29, No. 4 (1990), pp. 675-680.

G. van der Veen and W. Prins, Phys. Sci., Vol. 230 (1971) , pp. 70.

H. Tobushi, S. Hayashi, S. Kojima, "Mechanical properties of shape memory polymer of polyurethane series," *JSME Int. J.*, Ser. I. Vol. 35, No 3 (1992), pp.296-302.

Heitner-Wirguin, C. "Recent advances in perfluorinated ionomer membranes: Structure, properties and applications," *Journal of Membrane Science*, V 120, No. 1, pp. 1-33, 1996.

Hunter I. W., and S. Lafontaine, "A comparison of muscle with artificial actuators," *IEEE Solid-State Sensor and Actuator Workshop*, 1992, pp. 178-165.

Jolly, M.R., Carlson, J.D., Munoz, B.C., Bullions, T.A., "The magnetoviscoelastic response of elastomer composites of ferrous particles embedded in a polymer matrix," *J. Intel. Mat. Syst.*, vol. 7. No. 6 (1996), pp. 613-622.

Kornbluh, R. Pelrine R. and Joseph, J. " Elastomeric dielectric artificial muscle actuators for small robots," *Proceeding of the 3rd IASTED International Conference*, Concun, Mexico, June, 14-16, 1995.

Kuhn W., A. Ramel, D. H. Walters, G. Ebner, and H.J. Kuhn, "The production of mechanical energy from different forms of chemical energy with homogeneous and cross-striated high polymer systems," Adv. *Polym. Sci.*, Bd. 1 (1960), pp. 540-592.

Kuhn W., B. Hargitay, A. Katchalsky, and H. Eisenburg, "Reversible dilatation and contraction by changing the state of ionization of high-polymer acid networks," *Nature*, Vol. 165 (1950), pp. 514-516.

Zrinyi M., L. Barsi, D. Szabo, and H. G. Kilian, "Direct observation of abrupt shape transition in ferrogels induced by nonuniform magnetic field," *J. Chem. Phys.,* Vol. 106, No. 13 (1997), pp. 5685-5692.

Oguro K., N. Fujiwara, K. Asaka, K. Onishi, and S. Sewa, "Polymer electrolyte actuator with gold electrodes," Proceedings of SPIE's 6th Annual International Symposium on Smart Structures and Materials, Newport Beach, CA, paper 3669-39, 1-5 March, 1999

Oguro, K., Y. Kawami and H. Takenaka, "Bending of an Ion-Conducting Polymer Film-Electrode Composite by an Electric Stimulus at Low Voltage," *Trans. Journal of Micromachine Society*, Vol. 5, (1992) pp. 27-30.

Otero T. F., H. Grande, J. Rodriguez, "A new model for electrochemical oxidation of polypyrrole under conformational relaxation control," *J. Electroanal. Chem.*, Vol. 394 (1995), pp. 211-216.

Q. M . Zhang, V. Bharti, and X. Zhao, "Giant electrostriction and relaxor ferroelectric behavior in electron-irradiated poly(vinylidene fluoride-trifluorethylene) copolymer," *Science*, Vol. 280, pp.2101-2104 (1998).

R. E. Perline, R. D. Kornbluh, and J. P. Joseph, "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," *Sensor Actuat. A*, Vol. 64 (1998), p.77-85.

Roentgen, W.C., "About the changes in shape and volume of dielectrics, caused by electricity," *Ann. Phys. Chem.,* Vol. 11 (1880), pp.771-786.

S. Bednarek, "Susceptability of magnetodielectrics within an elastomer matrix to length changes in heterogeneous magnetic field," *Appl. Phys. A*, vol. 66, pp.643-650 (1998).

Sadeghipour, K., R. Salomon, and S. Neogi, "Development of a Novel Electrochemically Active Membrane and 'Smart' Material Based Vibration Sensor/Damper," *Smart Materials and Structures*, (1992) 172-179.

Sen, A., Scheinbeim, J.I., and Newman, B.A., "The effect of platicizer on the polarization of poly(vinylidene fluoride) films," *J. Appl. Phys.,* Vol.56, No.9, pp.2433-2439 (1984).

Shahinpoor M., Y. Bar-Cohen, J. O. Simpson and J. Smith, "Ionic Polymer-Metal Composites (IPMC) as Biomimetic Sensors, Actuators & Artificial Muscles- A Review," Smart Materials & Structures Journal, Vol. 7, No. 6, (December, 1998) pp. R15-R30

Shahinpoor, M., "Conceptual Design, Kinematics and Dynamics of Swimming Robotic Structures using Ionic Polymeric Gel Muscles," *Smart Materials and Structures*, Vol. 1, No. 1 (1992) pp. 91-94.

Shahinpoor, M., "Continuum electromechanics of ionic polymeric gels as artificial muscles for robotic applications," *Smart Materials and Structures*, Vol. 3, pp. 367-372, 1994.

Shiga. T. Okada, A., and Kurauchi, T., "Electroviscoelastic effect of polymer blends consisting of silicone elastomer and semiconducting polymer particles," *Macromolecules*, vol. 26, pp.6958-6963 (1993).

Shiga, T. "Deformation and viscoelastic behaviour of polymer gels in electric fields," *Adv. Polym. Sci.,* Vol. 134, pp. 131-163 (1997).

Steinberg I. Z., A. Oplatka, and A. Katchalsky, "Mechanochemical engines," *Nature*, vol. 210, (1966) pp.568-571.

Sussman M. V., "Mechanochemical availability," *Nature*, Vol. 256 (1975), pp. 195-198.

Tanaka T., I. Nishio, S.T. Sun, and S. U. Nishio, "Collapse of gels in an electric field," *Science*, vol. 218, pp. 467-469 (1982).

Yoshiko A., A, Mochizuki, T. Kawashima, S. Tamashita, K. Asaka and K. Oguro, "Effect on Bending Behavior of Counter Cation Species in Perfluorinated Sulfonate Membrane-Platinum Composite," *Polymers for Advanced Technologies*, Vol. 9 (1998), pp. 520-526.

Zhang, Q.M. , Bharti, V., Zhao, X., "Giant electrostriction and relaxor ferroelectric behaviour in electron-irradiated poly(vinylidene fluoride-trifluoroethylene) copolymer," *Science*, Vol. 280, (1998) pp. 2101-2103.

Zrinyi, M, Barsi, L., Buki, A., "Deformation of ferroegels induced by nonuniform magnetic fields," *J. Chem. Phys*., Vol. 104, No. 21 (1996), pp. 8750-8756.